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Ground-Water Issue: The Effects of Well Casing Material on Ground Water-Quality

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Abstract: The Regional Superfund Ground Water Forum is a group of ground-water scientists representing U.S. Environmental Protection Agency's (U.S. EPA's) Regional Offices, organized to exchange up-to-date information related to ground-water remediation at hazardous waste sites. Well casing materials used at hazardous waste sites is an issue identified by the forum as a concern of CERCLA decision makers. All aspects of a ground-water sampling program have the potential to affect the composition of a ground-water sample. The high degree of accuracy (parts per billion (ppb) range) required of some chemical analysis dictates that all potential sources of error of a ground-water sampling program be identified and sources of error in such aspects be minimized. Selection of the proper casing material for monitoring wells has been a subject of much controversy since the publication of the U.S.

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THE EFFECTS OF WELL CASING MATERIAL ON GROUND WATER-QUALITY

José L. Llopis[1]

INTRODUCTION

The Regional Superfund Ground Water Forum is a group of ground-water scientists representing U.S. Environmental Protection Agency's (U.S. EPA's[2]) Regional Offices, organized to exchange up-to-date information related to ground-water remediation at hazardous waste sites. Well casing materials used at hazardous waste sites is an issue identified by the forum as a concern of CERCLA decision makers.

To address this issue, this paper was prepared through support from the Environmental Monitoring Systems Laboratory-Las Vegas (EMSL-LV), under the direction of J. Lary Jack, with the support of the Superfund Technical Support Project. For further information, contact Ken Brown, EMSL-LV Center Director, at FTS 545-2270 or J. Lary Jack at FTS 545-2373.

All aspects of a ground-water sampling program have the potential to affect the composition of a ground-water sample. The potential for the introduction of sample error exists from the time drilling commences and continues to the time water samples are analyzed in the laboratory. The high degree of accuracy (parts per billion (ppb) range) required of some chemical analysis dictates that all potential sources of error of a ground-water sampling program be identified and sources of error in such aspects be minimized. One potential source of error is the interaction of the ground-water sample with material used in well casings for monitoring wells. Well casing materials may introduce error in a sample by interacting with water while it is still in the well and altering the water composition. Proper selection of casing materials used for ground-water monitoring wells is critical in minimizing errors introduced by this interaction. The purpose of this paper is to present a survey of results from laboratory and field investigations conducted by various researchers to determine the potential of different well casing materials to leach and/or sorb trace metals and organic compounds when in contact with ground water.

Selection of the proper casing material for monitoring wells has been a subject of much controversy since the publication of the U.S. EPA's Resource Conservation and Recovery Act (RCRA) Ground-Water Monitoring Technical Enforcement Guidance Document (TEGD) (U.S. EPA 1986). The TEGD suggests the use of polytetrafluoroethylene (PTFE, Teflon®) or stainless steel (SS) for sampling volatile organics in the saturated zone and further states "National Sanitation Foundation (NSF) or American Society for Testing and Materials (ASTM) approved polyvinylchloride (PVC) well casing and screens may be appropriate if only trace metals or nonvolatile organics are the contaminants anticipated". This statement suggests that PVC casing is not acceptable for collecting ground-water samples for volatile organic analysis.

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[2] For a list of abbreviations, see page 15.

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When the TEGD was published, it was a widely held view that PTFE was an inert material not capable of leaching or sorbing any substances that might bias the analytical results. However, several studies have been performed concluding that PTFE may react with water samples thus biasing the resulting analysis (Reynolds and Gillham, 1985; Parker et al., 1989). Investigations have also been conducted using many different types of casing materials to determine if these materials induce any statistically significant effects on ground-water samples. The best material, of course, would be one that would introduce the smallest error into the sample for the least cost. One of the largest drawbacks to using PTFE and SS for casing monitoring wells is their initial high cost. The high cost of PTFE and SS casing might cause a reduction in the number of wells at a site, the number of samples that can be analyzed, or the frequency of sampling, thus compromising the sampling program. It is important to determine if there are more economical casing materials available that can be substituted for PTFE or SS for ground-water monitoring programs.

SOURCES OF ERROR

Error can be introduced into the ground-water sample by casing materials with several processes including:

a. Chemical attack of the casing material.

b. Sorption and desorption.

c. Leaching of the casing material.

d. Microbial colonization and attack (Barcelona et al., 1985)

Before proceeding further, it is necessary to define the terminology used in this report. The terms "sorbed" or "sorption" are used many times in the literature to refer to the processes of adsorption and absorption especially when the exact mechanism is not known. Adsorption is defined as the adherence of atoms, ions, or molecules of a gas or liquid called the adsorbate onto the surface of another substance, called the adsorbent; whereas, absorption is the penetration of one substance (absorbate) into the inner structure of another called the absorbent. In this report, rather than distinguishing between the processes of adsorption and absorption, the term sorbed will be used synonymously with both processes, unless otherwise noted. Desorption refers to the process of removing a sorbed material from the solid on which it is sorbed. Leaching refers to the removal or extraction of soluble components of a material (i.e., casing material) by a solvent (Sax and Lewis, 1987).

Casing material in contact with a liquid has the potential to allow either leaching and/or sorption. Factors influencing sorption of organics and metals are discussed by Jones and Miller (1988) and Massee et al., (1981), respectively. These factors include:

1. The surface area of the casing. The greater the ratio of casing material surface area to the volume of adsorbate the greater the sorption potential.
2. Nature of the analyte (chemical form and concentration).
3. Characteristics of the solution. This includes factors such as pH, dissolved material (e.g., salinity, hardness), complexing agents, dissolved gasses (especially oxygen, which may influence the oxidation state), suspended matter (competitor in the sorption process), and microorganisms (e.g., trace element take-up by algae).
4. Nature of the casing material (adsorbent). This includes factors such as the chemical and physical properties of the casing material.
5. External factors. These factors include temperature, contact time, access of light, and occurrence of agitation.

According to Barcelona et al., (1988) considerations for selecting casing material should also include the subsurface geochemistry and the nature and concentration of the contaminants of interest. They also state that strength, durability, and inertness of the casing material should be balanced with cost considerations. Ford (1979) summarized factors related to the analyte that can affect adsorption (Table 1).

TABLE 1. FACTORS AFFECTING ADSORPTION

1. An increasing solubility of the solute in the liquid carrier decreases its adsorbability.
2. Branched chains are usually more adsorbable than straight chains. An increasing length of the chain decreases solubility.
3. Substituent groups affect adsorbability.

Substituent Group	Nature of Influence
Hydroxyl	Generally reduces absorbability; extent of decrease depends on structure of host molecule.
Amino	Effect similar to that of hydroxyl but somewhat greater. Many amino acids are not adsorbed to any appreciable extent.
Carbonyl	Effect varies according to host molecule; glyoxylic are more adsorbable than acetic but similar increase does not occur when introduced into higher fatty acids.
Double Bonds	Variable effect as with carbonyl.
Halogens	Variable effect.
Sulfonic	Usually decreases adsorbability.
Nitro	Often increases adsorbability.
Aromatic Rings	Greatly increases adsorbability.

4. Generally, strong ionized solutions are not as adsorbable as weakly ionized ones; i.e., undissociated molecules are in general preferentially adsorbed.
5. The amount of hydrolytic adsorption depends on the ability of the hydrolysis to form an adsorbable acid or base.
6. Unless the screening action of the adsorbent pores intervene, large molecules are more sorbable than small molecules of similar chemical nature. This is attributed to more solute-adsorbent chemical bonds being formed, making desorption more difficult.
7. Molecules with low polarity are more sorbable than highly polar ones.

(Source: Ford, 1977)

Berens and Hopfenberg (1981) conducted an investigation to determine a correlation between diffusivity and size and shape of the penetrant molecules. Their study indicated that as the diameter of "spherical" penetrant molecules increased, the diffusivity decreased exponentially. Another finding of the study was that flattened or elongated penetrant molecules such as n-alkanes had greater diffusivities than spherical molecules of similar volume or molecular weight. This may indicate that elongated molecules can move along their long axis when diffusing through a polymer.

Reynolds and Gillham (1985) used a mathematical model to predict the absorption of organic compounds by the different polymer materials. Curves based on their model were fit to experimental data and showed reasonable agreement. This agreement supports their concept that uptake is the result of absorption. They also determined that no relationship was found between the order of absorption and readily available parameters such as aqueous solubility or octanol/water partitioning coefficient. They concluded that predicting the amount of absorption for a particular organic compound was not possible at that time.

Gillham and O'Hannesin (1990) attempted to predict the rate of uptake of benzene, toluene, ethylbenzene, and p-, m-, and o-xylene onto samples SS316, PTFE, rigid PVC, flexible PVC, polyvinylidene fluoride (PVDF), flexible PE, and FRE employing the same model as that used by Reynolds and Gillham (1985). Their results showed the diffusion model data fitted their experimental data quite well, suggesting the sorption mechanism was absorption into the polymer materials agreeing with the results of Reynolds and Gillham (1985). They also determined, that for the organic compounds used in this study, the rate of uptake increased with increasing hydrophobicity of the organic compound and varied with the physical characteristics of the polymer casing material.

TYPES OF CASING MATERIALS

A variety of materials may be used for casing and screening ground-water monitoring wells. These materials include glass and metallic and synthetic materials. Rigid glass has the least potential for affecting a sample and is the material of choice for sampling organics (Pettyjohn et al., 1981). However, because the use of glass as a casing material is impractical for field applications because of its brittleness, it will not be further considered in this report. Instead, this report will focus on the metallic and synthetic materials most commonly used for monitoring well construction.

Metals

Metals are often chosen as casing materials because of their strength. Metals used for casing include SS, carbon steel, galvanized steel, cast iron, aluminum, and copper. The various metals used for well casings may react differently to different compounds. Reynolds et al., (1990) conducted a study using SS, aluminum, and galvanized steel to determine their potential to cause problems in samples collected for analysis for halogenated hydrocarbons. The metals were subjected to aqueous solutions of 1,1,1-trichloroethane (1,1,1-TCA), 1,1,2,2-tetrachloroethane (1,1,2,2,-TET), hexachloroethane (HCE), bromoform (BRO), and tetrachloroethylene (PCE) for periods up to 5 weeks. The study indicated that, of the metals used, SS was the least reactive followed by aluminum and galvanized steel. Stainless steel caused a 70 percent reduction of BRO and HCE after 5 weeks. Aluminum caused over a 90 percent reduction for all but one of the compounds while galvanized steel showed over a 99 percent reduction for all of the compounds.

Many investigations have shown that errors may be introduced into the water sample as a result of using metal casings. For instance, Marsh and Lloyd (1980) determined steel-cased wells modified the chemistry of the formation water. They state that trace element concentrations of the ground water collected from the wells were not representative of the aquifer conditions and did not recommend the use of steel casing for constructing monitoring wells. They suspected that reactions between the ground water and the steel casing raise the pH of the water which causes the release of metal ions into solution. Pettyjohn et al., (1981) found metals strongly adsorb organic compounds. For example, they claim that DDT is strongly adsorbed even by SS. Hunkin et al., (1984) maintain that steel-cased wells are known to add anomalously high iron and alloy levels as well as byproducts of bacterial growth and corrosion to a sample. Houghton and Berger (1984) discovered that samples from steel-cased wells were enriched in cadmium (Cd), chromium (Cr), copper (Cu), iron, manganese, and zinc (Zn) relative to samples obtained from plastic-cased wells.

Stainless steel is one type of metal used for casing and that appears to have a high resistance to corrosion. In fact, the U.S. EPA (1987) states that SS is the most chemically resistant of the ferrous materials. Two types of SS extensively used for groundwater monitoring are stainless steel 304 (SS304) and stainless steel 316 (SS316). These are classified as austenitic type SS and contain approximately 18 percent chromium and 8 percent nickel. The chemical composition of SS304 and SS316 is identical with the exception being SS316 which contains 2-3 percent molybdenum. Brainard-Kilman (1990) indicate SS316 has improved resistance to sulfuric and saline conditions and better resistance to stress-corrosion.

The corrosion resistance of SS is due to a passive oxide layer which forms on the surface in oxidizing environments. This protective layer is only a few molecules thick. It recovers quickly even if removed by abrasion (Fletcher 1990). However, several investigators note that SS is still susceptible to corrosion. Under corrosive conditions, SS may release iron, chromium, or nickel (Barcelona et al., 1988). Hewitt (1989a) found in a laboratory study that samples of SS316 and SS304 were susceptible to oxidation at locations near cuts and welds. When these cuts and welds are immersed in ground water, this surface oxidation provides active sites for sorption and also releases impurities and major constituents. SS may be sensitive to the chloride ion, which can cause pitting corrosion, especially over long term exposures under acidic conditions (U.S. EPA, 1987).

Parker et al., (1989) evaluated samples of SS304 and SS316 for their potential to affect aqueous solutions of 10 organic compounds. The 10 organics used in the study were RDX, trinitrobenzene (TNB), c-1,2-DCE, t-1,2-DCE, m-nitrotoluene (MNT), TCE, MCB, o-dichlorobenzene (ODCB),

p-dichlorobenzene (PDCB), and m-dichlorobenzene (MDCB) at concentrations of 2 mg/L. Their study indicated the SS well casings did not affect the concentration of any of the analytes in solution.

Synthetic Materials

Synthetic materials used for casing evaluation include PTFE, PVC, polypropylene (PP), polyethylene (PE), nylon, fiberglass reinforced epoxy (FRE), and acrylonitrile butadiene styrene (ABS). The two most commonly used synthetic casing materials are PVC and PTFE. Very little information regarding the suitability of FRE as a casing material is presently available in the literature; however, a 3-week dwell-time study conducted by Cowgill (1988) indicated that FTFE revealed no detectable quantities of the substances used in its manufacture. Hewitt (1989a and 1989b) determined that PTFE was the material of choice for sampling inorganic compounds whereas, Barcelona (1985) recommends PTFE for most all monitoring applications.

PTFE is a man-made material composed of very long chains of linked fluorocarbon units. PTFE is considered as a thermoplastic with unique properties. It is very inert chemically and no substance has been found that will dissolve this polymer (The Merck Co. Inc. 1984). The Merck Co. Inc. (1984) reports that nothing sticks to this polymer. This antistick property may prevent grouts from adhering to PTFE casing and prevent the development of an effective seal around a PTFE casing. PTFE also has a very wide useful temperature range, -100° to +480° F; however, for most ground-water monitoring applications these extremes of temperature would rarely be encountered.

PTFE has a low modulus of elasticity making the screened portion PTFE casing prone to slot compression under the weight of the well casing above. PTFE is also very flexible and the casing sometimes has the tendency to become "crooked" or "snake" especially in deep boreholes. Special procedures are then required to install the casing. Morrison (1986) and Dablow et al., (1988) discuss different techniques used to overcome installation problems inherent to PTFE wells. PTFE also has the tendency to stretch thus, making PTFE cased wells susceptible to leaks around threaded joints.

PVC casing is an attractive alternative to PTFE and SS because it is inexpensive, durable, lightweight, has better modulus and strength properties than PTFE, and is easy to install. However, these characteristics alone do not justify its use as a monitoring well casing material. The casing material must not react significantly with the surrounding ground water, leach, sorb, or desorb any substances that might introduce error into the sample. Many studies have been conducted comparing PVC to other casing materials to determine its suitability for use in monitoring wells.

Various compounds are added to the basic PVC polymer during the manufacturing process of rigid PVC. These compounds include thermal stabilizers, lubricants, fungicides, fillers, and pigments (Boettner et al., 1981; Packham, 1971). It is presumed that the additional compounds have the potential to leach into the ground water. Tin, found in some thermal stabilizers, is one of the compounds suspected of leaching from PVC. Boettner et al., (1981) found that as much as 35 ppb dimethyltin could be leached from PVC in a 24-hour period. Other compounds used as thermal stabilizers, and potential sources of contaminants, are calcium, Zn, and antimony.

Another compound suspected of leaching from PVC casing is residual vinyl chloride monomer (RVCM). According to Jones and Miller (1988), 1-inch diameter Schedule 40 PVC pipe containing 10-ppm RVCM leaches undetectable quantities (at the 2.0-ppb sensitivity level) of vinyl chloride into stagnant water retained in the pipe. They also report that 98 percent of the PVC casing currently manufactured in North America contains less than 10-ppm RVCM and most casing contains less than 1 ppm RVCM. This implies that a 1-inch diameter pipe should leach 2.0-ppb or less RVCM. The amount of RVCM leached would also decrease as the casing diameter increased because of the lower specific surface. Specific surface (R) is defined as the ratio of the surface area of the casing material in contact with the solution, to the volume of the solution. Thus, as casing diameter increases, the specific area decreases.

The NSF (1989) has established maximum permissible levels (MPL) for many chemical substances used in the manufacturing of PVC casing (Table 2). These levels are for substances found in low pH extractant water following extraction procedures described by the NSF (1989). Sara (1986) recommends the use of NSF-tested and approved PVC formulations to reduce the possibility of leaching RVCM, fillers, stabilizers, and plasticizers.

TABLE 2. MAXIMUM PERMISSIBLE LEVELS FOR CHEMICAL SUBSTANCES

Substances	MPL mg/L	Action levels mg/L
Antimony	0.05	
Arsenic	0.050	
Cadmium	0.005	
Copper	1.3	
Lead	0.020	
Mercury	0.002	
Phenolic Substances		0.05[1]
Tin	0.05	
Total Organic Carbon		5.0[1]
Total Trihalomethanes	0.10	
Residual Vinyl Chloride Monomer*	3.2	2.0[2]

** In the finished product ppm (mg/kg).*

[1] This is an action level. If the level is exceeded, further review and/or testing shall be initiated to identify the specific substance(s), and acceptance or rejection shall be based on the level of specific substances in the water.

[2] Additional samples shall be selected from inventory and tested to monitor for conformance to the MPL.

(Source: NSF Standard Number 14)

Common practice was to use cleaner-primers and solvent cements to join PVC casing sections used in monitoring wells. Cements used for joining casing sections dissolve some of the polymer and "weld" the casing sections together. Past studies showed a correlation between certain organic compounds found in ground-water samples and the use of PVC solvent cement (Boettner et al., 1981; Pettyjohn et al., 1981; Sosebee et al., 1983; Curran and Tomson, 1983). Sosebee et al., (1983) found high levels of tetrahydrofuran, methylethylketone, methylisobutylketone, and cyclohexanone, the major constituents of PVC primer and adhesive, in water surrounding cemented casing joints months after installation. Sosebee et al., (1983) determined that besides contaminating the ground-water sample these contaminants have the potential to mask other compounds found in the ground water during laboratory analysis. Boettner et al., (1981) found, in an experiment in which solvent cement was used for joining PVC casing, methylethylketone, tetrahydrofuran, and cyclohexanone leaching into water supplies after more than 2 weeks of testing.

Houghton and Berger (1984) conducted a study to determine the effects of well casing composition and sampling method on water-sample quality. Three wells were drilled on 20-ft centers to a depth of 60 feet and cased with PVC, ABS, and steel. Samples collected from the wells indicated ABS-cased wells were enriched in dissolved organic carbon by 67 percent and in total organic carbon (TOC) by 44 percent relative to samples from the steel-cased well. The PVC-cased well was enriched in dissolved organic carbon and TOC by approximately 10 percent relative to the steel-cased well. The high TOC concentrations found in the ABS and PVC casings are suspected to have been derived from the cement used to connect the casing sections.

Other compounds suspected of leaching from PVC and into ground water are chloroform ($CHCl_3$) and carbon tetrachloride (CCL_4). Desrosiers and Dunnigan (1983) determined that PVC pipe did not leach $CHCl_3$ or CCL_4 into deionized, demineralized, organic-free water, or tap water in the absence of solvent cement even after a 2-week dwell time.

PVC primers and adhesives should not be used for joining PVC monitoring well casing sections. The recommended means for joining PVC casing is to use flush-joint threaded pipe casing. Foster (1989) provides a review of ASTM guideline F480-88A which describes in detail the standard PVC flush-joint thread.

Junk et al., (1984) passed "organic free" water through PE, PP, latex, and PVC tubings, and a plastic garden hose. They found o-creosol, naphthalene, butyloctylfumarate, and butylchloroacetate leaching from the PVC tubing. These contaminants are related to plasticizers which are added to PVC during the manufacturing process to make it more flexible. Rigid PVC well casing contains a much smaller quantity of plasticizer and should be less prone to leaching contaminants (Jones and Miller, 1988).

LEACHING AND SORPTION STUDIES

Many studies have been undertaken to determine the interaction of different casing materials with volatile organic compounds (VOCs) and trace metals. Much of the research has been aimed at determining whether PVC can be used as a substitute for more expensive materials such as PTFE, FRE, and SS. A review of the literature investigating the potential effects of assorted well casing materials on ground-water samples is presented below.

Organic Studies

Lawrence and Tosine (1976) found that PVC was effective for adsorbing polychlorinated biphenyls (PCB) from aqueous sewage solutions. They reported that the low solubility and hydrophobic nature of the PCBs makes them relatively easy to adsorb from aqueous solution. Parker et al., (1989) suggest the PVC appears to be effective only in sorbing PCBs at concentrations close to their solubility limits.

Pettyjohn et al., (1981) discuss materials used for sampling organic compounds. They provide a list of preferred materials for use in sampling organic compounds in water. Their choice in order of preference is glass, PTFE, SS, PP, polyethylene, other plastics and metals, and rubber. They do not indicate whether the materials in the list were sections of rigid or flexible tubing or what testing procedures were followed. They note that experimental data on the sorption and desorbtion potential of casing materials using varied organic compounds were not available.

Miller (1982) conducted a laboratory study in which one of the objectives was to quantify adsorption of selected organic pollutants on Schedule 40 PVC 1120, low density PE, and PP well casing materials. These materials were exposed to six organic pollutants and monitored for adsorption over a 6-week period. The VOCs used, along with their initial concentrations, were BRO (4 ppb), PCE (2 ppb), trichloroethylene (TCE) (3 ppb), trichlorofluoromethane (2 ppb), 1,1,1-TCA (2 ppb), and 1,1,2-trichloroethane (14 ppb). The results showed that PVC adsorbed only PCE. The PVC adsorbed approximately 25 to 50 percent of the PCE present. The PP and PE samples adsorbed all six of the organics in amounts ranging from 25 to 100 percent of the amount present.

Curran and Tomson (1983) compared the sorption potential of PTFE, PE, PP, rigid PVC (glued and unglued), and Tygon (flexible PVC). The procedures used in this investigation consisted of pumping 20 L of organic-free water with a 0.5-ppb naphthalene spike through each tubing at a rate of 30 mL/min. The tests showed that 80 to 100 percent of the naphthalene was recovered from the water for all materials except Tygon tubing. Tygon tubing sorbed over 50 percent of the naphthalene. PTFE showed the least contaminant leaching of the synthetic materials tested. They concluded that PVC can be used as a substitute for PTFE in monitoring wells if the casing is properly washed and rinsed with room temperature water before installation. They also conclude that PE and PP could suitably be used as well casings.

Barcelona et al., (1985) presented a ranking of the preferred rigid materials based on a review of manufacturers' literature and a poll of the scientific community. The list presented by Barcelona et al., (1985) recommended the following casing materials in order of decreasing preference: PTFE, SS316, SS304, PVC, galvanized steel, and low carbon steel. Table 3 presents recommended casing materials tabulated in Barcelona et al., (1985) along with specific monitoring situations.

TABLE 3. RECOMMENDATIONS FOR RIGID MATERIALS IN SAMPLING APPLICATIONS
(In decreasing order of preference)

Material	Recommendations
PTFE (Teflon®)	Recommended for most monitoring situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted hydrogeologic conditions. Virtually an ideal material for corrosive situations where inorganic contaminants are of interest.
Stainless Steel 316 (flush threaded)	Recommended for most monitoring (flush threaded) situations with detailed organic analytical needs, particularly for aggressive, organic leachate impacted by hydrogeologic conditions.
Stainless Steel 304 (flush threaded)	May be prone to slow pitting corrosion in contact with acidic high total dissolved solids aqueous solutions. Corrosion products limited mainly to Fe and possibly Cr and Ni.
PVC (flush threaded) other noncemented connections, only NSF-approved materials for casing or potable water applications.	Recommended for limited monitoring situations where inorganic contaminants are of interest and it is known that aggressive organic leachate mixtures will not be contacted. Cemented installations have caused documented interferences. The potential for interaction and interferences from PVC well casing in contact with aggressive aqueous organic mixtures is difficult to predict. PVC is not recommended for detailed organic analytical schemes.
	Recommended for monitoring inorganic contaminants in corrosive, acidic inorganic situations. May release Sn or Sb compounds from the original heat stabilizers in the formulation after long exposure.
Low Carbon Steel Galvanized Steel Carbon Steel	May be superior to PVC for exposures to aggressive aqueous organic mixtures. These materials must be very carefully cleaned to remove oily manufacturing residues. Corrosion is likely in high dissolved solids acidic environment, particularly when sulfides are present. Products of corrosion are mainly Fe and Mn, except for galvanized steel which may release Zn and Cd. Weathered steel surfaces present very active sites for trace organic and inorganic chemical species.

(Source: Barcelona et al., 1985)

Reynolds and Gillham (1985) conducted a laboratory study to determine the effects of five halogenated compounds on six polymer materials. The five compounds used in this study were 1,1,1-TCA, 1,1,2,2-TET, HCE, BRO, and PCE. The polymer materials studied were PVC rod, PTFE tubing, nylon plate, low density PP tubing, low density PE tubing, and latex rubber tubing. The authors evaluated nylon plate because nylon mesh is often used as a filter material around screened portions of wells. Latex rubber tubing was evaluated as a material that represented maximum absorption. The materials were tested under static conditions to simulate water standing in the borehole. Measurements were made over contact times that ran from 5 minutes to 5 weeks.

Results of the study are presented in Table 4. The results show that PVC absorbed four of the five compounds; however, the rate of absorption was relatively slow (periods of days to weeks). Given this slow absorption rate, they do not consider there would be significant absorption by PVC if wells were purged and sampled the same day. The one organic compound that was not absorbed significantly by the PVC during the 5-week test period was 1,1,1-TCA. The loss of BRO to PVC in this study was approximately 43 percent after 6 weeks; whereas, Miller (1982), in a similar experiment, indicated no losses from solution over the same time period.

PTFE showed absorption of four of the five compounds tested. There was no significant absorption of BRO over the 5-week test period. It is noted that approximately 50 percent of the original concentration of PCE was absorbed within an 8-hour period. The concentration of this compound may be affected even when the time between purging and sampling is short.

TABLE 4. TIME AT WHICH ABSORPTION REDUCED THE RELATIVE CONCENTRATION IN SOLUTION TO 0.9

PVC	1,1,1-TCA	1,1,2,2-TET	BRO	HCE	PCE
	>5 weeks	~2 weeks	~3 days	~1 day	~1 day
PTFE	BRO	1,1,2,2-TET	1,1,1-TCA	HCE	PCE
	>5 weeks	~2 weeks	~1 day	~1 day	<5 minutes
Nylon	1,1,1-TCA	1,1,2,2-TET	BRO	PCE	HCE
	~6 hours	~1 hour	~30 minutes	~30 minutes	<5 minutes
PP	1,1,2,2-TET	BRO	1,1,1-TCA	HCE	PCE
	~4 hours	~1 hour	~1 hour	<5 minutes	<5 minutes
PE	1,1,2,2-TET	BRO	1,1,1-TCA	HCE	PCE
	~15 minutes	<5 minutes	<5 minutes	<5 minutes	<5 minutes
Latex	1,1,2,2-TET	1,1,1-TCA	BRO	PCE	HCE
Rubber	<5 minutes	<5 minutes	<5 minutes	<5 minutes	<5 minutes

(Source: Reynolds and Gillham, 1985)

The other casing materials demonstrated significant absorption losses within minutes to a few hours after exposure to the organic compounds. The use of nylon, latex rubber, PP, and PE as a well casing material will cause a significant reduction in the concentration of the organic compounds even when the time between purging and sampling is short. They state that agreement between the model study and experimental results support the concept that absorption of the organic compounds by the polymers occur by sorption/dissolution of the compounds into the polymer surface followed by diffusion into the polymer matrix.

Parker and Jenkins (1986) conducted a laboratory study to determine if PVC casing was a suitable material for monitoring low levels of the explosives 2,4,6-trinitrotoluene (TNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), octahydro-1,3,5,7-tetranitro 1,3,5,7-tetrzocine (HMX), and 2,4-dinitrotoluene (DNT). Samples of PVC casing were placed in glass jars containing an aqueous solution of TNT, RDX, HMX, and DNT. After 80 days, the solution was tested to determine the concentration of TNT, RDX, HMX, and DNT left in solution. After the 80 days, the solutions containing RDX, HMX, and DNT showed little loss, whereas TNT showed a significant loss. PVC casing was tested under sterile and nonsterile conditions in a 25-day experiment to determine whether microbial degradation or sorption by PVC was the cause for losses of TNT, RDX, HMX, and DNT. Results indicated that the loss of TNT in the test was caused by microbial activity rather than to adsorption. The increased microbial activity may be caused by bacteria initially present on the unsterilized PVC casing, increased surface area for colonization provided by the PVC surface, leaching of nutrients from the casing increasing the growth of bacteria, and the rate of biodegradation.

Parker and Jenkins (1986) do not consider PVC casing to significantly affect ground-water samples when monitoring for TNT, RDX, DNT, and HMX if the time between purging of the well and sampling is short. They concluded PVC is an acceptable casing material for ground-water monitoring of TNT, RDX, DNT, and HMX.

Sykes et al., (1986) performed a laboratory study to determine if there was a significant difference in the sorption potential between PVC, PTFE, and SS316 when exposed to methylene chloride (dichloromethane or DCM), 1,2-dichloroethane (1,2-DCA), trans-1,2-dichloroethylene (t-1,2-DCE), toluene, and chlorobenzene (MCB). Samples of the various well casing materials were placed in jars containing aqueous solutions of the solvents at concentrations of approximately 100 ppb. The concentration of each solvent was determined after 24 hours and again after 7 days. The study concluded that there were no statistically different chemical changes in the solutions exposed to PVC, PTFE, and SS316 casing. Thus, it could be presumed that PVC, PTFE, or SS316 are suitable casing materials for monitoring DCM, 1,2-DCA, t-1,2-DCE, toluene, and MCB when the period between well purging and sampling is less than 24 hours.

Barcelona and Helfrich (1986) conducted a field study at two landfills to determine the effects of different casing materials on sample quality. Wells were constructed upgradient and downgradient of each of the two landfill sites. The wells at Landfill 1 were constructed of PTFE, PVC, and SS304; whereas, the wells at Landfill 2 were constructed of PVC and SS.

They observed that the downgradient SS and PTFE wells at Landfill 1 showed higher levels of TOC than did the PVC wells. The upgradient wells at Landfill 1 showed no significant difference among casing material type. TOC sampling at Landfill 2 showed similar results; however, no significant differences among material types were determined either upgradient or downgradient of the landfill.

Levels of 1,1-dichloroethane (1,1-DCA) and cis-1,2-dichloroethylene (c-1,2-DCE) were significantly higher for the downgradient SS wells than for PTFE and PVC cased wells at Landfill 1. They suspect that PTFE and PVC tend to have a greater affinity for these organic compounds than does SS.

At Landfill 2 they noted greater levels of 1,1-DCA and total volatile halocarbons in the PVC wells than in the SS wells. They hypothesize that the higher levels of the organic compounds found in the water samples from the PVC cased well may be caused by the sorptive and leaching properties of PVC which tend to maintain a higher background level of organic compounds in the ground water relative to SS. They did not suspect the SS and PVC wells at Landfill 2 are intercepting ground water of different quality since the wells are approximately 4 feet apart. The authors conclude that well casing materials exert significant, though unpredictable effects on TOC and specific VOC determinations. Parker et al., (1989) suspect that a larger statistical base is needed before such conclusions can be drawn. Parker et al., (1989) also suggest the possibility that differences in well construction methods may have had an effect on the quality of these water samples.

Gossett and Hegg (1987) conducted a laboratory test to determine the effects of using a PVC bailer, a PTFE bailer, and an ISCO Model 2600 portable pump on the recovery of $CHCl_3$, benzene, and 1,2-DCA. The effect on recovery of VOCs was studied by varying the lift height and the casing material. The casing materials consisted of either PVC or SS. In their conclusion they state that either PVC or SS would be suitable for collecting VOC samples.

Parker et al., (1989) performed a laboratory study to compare the performance of PVC, SS304, SS316, and PTFE subjected to aqueous solutions of RDX, trinitrobenzene (TNB), c-1,2-DCE, t-1,2-DCE, m-nitrotoluene (MNT), TCE, MCB, o-dichlorobenzene (ODCB), p-dichlorobenzene (PDCB), and m-dichlorobenzene (MDCB) at concentrations of 2 mg/L. A biocide was added to the samples to eliminate possible losses due to biodegradation.

Prior to the experiment, they conducted a test to determine if the casing materials were capable of leaching any compounds into water. Samples of casing material were placed in vials containing well water and allowed to stand for 1 week. No evidence of materials leaching from any of the casing materials was noted.

Casing samples were placed in sample jars containing an aqueous solution of the organic compounds and sampled ini-

tially and at intervals between 1 hour and 6 weeks. Table 5 presents results after a 1-hour, 24-hour, and 6-week dwell time. The test results indicated that after 6 weeks PTFE had sorbed significant amounts of all the compounds with the exception of RDX and TNB. In the same time period, PVC showed significant sorption of TCE, MCB, ODCB, PDCB and MDCB. In each one of the cases where the PVC and PTFE both sorbed significant amounts of analytes, PTFE always had the greatest sorption rate. After 6 weeks, the SS samples exhibited no significant sorption of the tested compounds.

At the 24-hour mark, PTFE and PVC had experienced significant sorption of all the compounds with the exception of RDX, TNB, and MNT. For the compounds sorbed by PTFE and PVC, PTFE had the higher rate of uptake with the exception of c-1,2-DCE. SS showed no significant sorption of any of the compounds tested. It appears that PTFE cased wells will introduce a greater bias into ground-water samples than those cased with PVC if the time between sampling and purging is 24 hours.

They also conducted a desorption experiment on the samples that had sorbed organics for 6 weeks. After 3 days of testing, the PVC and PTFE samples showed desorption of analytes sorbed in the previous experiment. The desorption study showed that PTFE, in general, showed a greater loss of analytes than PVC.

Jones and Miller (1988) conducted laboratory experiments to evaluate the adsorption and leaching potential of Schedule 40 PVC (PVC-40), Schedule 80 PVC (PVC-80), ABS, SS, Teflon-PFA, Teflon-FEP, PTFE, and Kynar-PVDF. Organic compounds used in this experiment were 2,4,6-trichlorophenol (2,4,6-TCP), 4-nitrophenol, diethyl pthalate, acenaphthene, naphthalene, MDCB, 1,2,4-trichlorobenzene, and hexachlorobenzene. Samples of casing material were placed into glass vials each containing an organic compound having an approximate initial concentration of 250 ppb.

In their first experiment, the organic compounds were mixed with neutral pH ground water. The batches were sampled immediately and then at intervals of 1-, 3-, and 6-weeks. The results showed that there was no appreciable change in adsorption of the compounds after 1 week except for 2,4,6-TCP, which totally adsorbed after 3 weeks. The results also indicate that PTFE might be less likely to adsorb these compounds. Jones and Miller (1988) also point out that at the concentrations used in this study, PTFE, PVC-40, and PVC-80 exhibited very little difference in the amounts of adsorption.

In their second experiment, Jones and Miller (1988) attempted to determine the amount of the adsorbed compounds that would be released back into uncontaminated ground water after a 6-week exposure time. After a 2-week period, very little release of organic contaminants was observed. They state that only zero to trace amounts of the sorbed contaminants were desorbed into the noncontaminated ground water. Only PVC-80 and Teflon-PFA desorbed naphthalene.

They repeated their adsorption and leaching experiments using polluted ground water with a pH of 3.0. The adsorption experiment showed that, with the exception of ABS casing, the casing materials showed less adsorption at the contaminated low pH level than at the noncontaminated neutral pH level. One possible explanation is there could be stronger binding and

TABLE 5. NORMALIZED* CONCENTRATION OF ANALYTES FOR FOUR WELL CASINGS WITH TIME

Analyte	Treatment	1 hour	24 hours	6 weeks
RDX	PTFE	1.03	1.00	0.99
	PVC	1.01	0.98	1.00
	SS304	0.99	1.01	0.98
	SS316	1.01	1.01	1.00
TNB	PTFE	1.01	1.00	1.01
	PVC	1.01	0.98	1.02
	SS304	0.99	1.00	1.00
	SS316	1.02	1.01	1.02
c-1,2-DCE	PTFE	1.01	0.96†	0.79†
	PVC	1.00	0.95†	0.90
	SS304	0.97	1.00	0.98
	SS316	0.95	1.00	0.99
t-1,2-DCE	PTFE	1.00	0.88†	0.56†
	PVC	1.00	0.93†	0.83
	SS304	0.95†	1.00	1.00
	SS316	1.00	1.00	1.00
MNT	PTFE	1.03	0.99	0.90†
	PVC	1.02	0.98	0.94
	SS304	1.00	1.01	1.07
	SS316	1.02	1.02	0.99
TCE	PTFE	1.00	0.85†	0.40†
	PVC	1.01	0.94†	0.88†
	SS304	0.96	1.01	0.99
	SS316	1.00	1.00	1.00
MCB	PTFE	1.01	0.90†	0.51†
	PVC	1.01	0.95†	0.86†
	SS304	0.98	1.00	0.99
	SS316	0.99	1.01	0.99
ODCB	PTFE	1.01	0.88†	0.43†
	PVC	1.02	0.94†	0.86†
	SS304	0.98	1.00	1.00
	SS316	1.01	1.01	1.00
PDCB	PTFE	0.92†	0.77†	0.26†
	PVC	0.95	0.92†	0.80†
	SS304	0.91†	1.00	1.02
	SS316	0.94	1.00	1.02
MDCB	PTFE	1.00	0.78†	0.26†
	PVC	1.02	0.92†	0.80†
	SS304	0.99	1.00	1.02
	SS316	1.03	1.00	1.01

** The values given here are determined by dividing the mean concentration of a given analyte at a given time and for a particular well casing by the mean concentration (for the same analyte) of the control samples taken at the same time.*

† Values significantly different from control values.

(Source: Parker et al., 1989)

more preferential complexing of the experimental pollutants with other pollutants in the contaminated ground water. Another, more likely explanation, is that there is a relationship between the extent of adsorption, pH, and pK, with a maximum adsorption occurring when the pH is approximately equal to pK. They explain that as the pH decreases, the hydrogen ion concentration increases and the adsorption tends to decrease, suggesting a replacement of the adsorbed compound by the more preferentially adsorbed hydrogen ions.

Jones and Miller (1988) concluded there is no clear advantage to the use of one particular well casing material over the others for the organics used in the study. Well purging procedures, sampling device selection and composition, and sample storage are probably of greater influence to sample integrity and representativeness than well casing material selection. They found the amount of adsorption generally correlates with the solubility of the chemical independent of the well casing material.

Gillham and O'Hannesin (1990) conducted a laboratory study to investigate the sorption of six monoaromatic hydrocarbons onto/into seven casing materials. The six organic compounds used were benzene, toluene, ethylbenzene, and p-, m-, and o-xylene. The seven casing materials used in the evaluation were SS316, PTFE, rigid PVC, flexible PVC, polyvinylidene fluoride (PVDF), flexible PE, and FRE. The materials were placed in vials containing an aqueous solution of all six organic materials. Concentrations of the organics in the solution ranged between 1.0 and 1.4 mg/L. Sodium azide (0.05 percent), a biocide, was added to the solution to prevent biodegradation of the organics. The solutions were sampled 14 times from 5 minutes to 8 weeks.

Results of the study are presented in Table 6 and indicate that SS is the most favorable casing material for sampling organics. Stainless steel showed no significant uptake after an 8-week exposure period; whereas, all the polymer materials adsorbed all the organic compounds to some degree. The order of magnitude of adsorption for the various polymer materials tested was flexible PVC > PE > PTFE > PVDF > FRE > rigid PVC (from greatest to least sorption). Flexible tubing materials showed substantial uptake after 5 minutes of exposure. Rigid PVC showed the lowest rate of uptake of the polymer materials.

TABLE 6. TIME INTERVAL WITHIN WHICH THE CONCENTRATION PHASE FOR THE COMPOUND AND CASING MATERIAL BECAME SIGNIFICANTLY DIFFERENT FROM 1.0

	Time, hours					
Material	Benzene	Toluene	Ethyl-benzene	m-Xylene	o-Xylene	p-Xylene
SS316	>1344					
PVC (rigid)	48 - 96	24 - 48	12 - 24	12 - 24	12 - 24	12 - 24
FRE	24 - 48	3 - 6	0.1 - 1.0	3 - 6	3 - 6	3 - 6
PVDF	24 - 48	3 - 6	1 - 3	1 - 3	0.1 - 1.0	1 - 3
PTFE	24 - 48	3 - 6	1 - 3	3 - 6	6 - 12	1 - 3
PE	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1
PVC (flexible)	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1	0 - 0.1

(Source: Gillham and O'Hannesin, 1990)

Gillham and O'Hannesin (1990) conclude all of the polymer materials tested, except flexible PVC and PE, are suitable casing materials in monitoring wells. This is based on selection of an appropriate casing diameter and an appropriate interval between purging and sampling. They state rigid PVC is the most favorable polymer material for casing in monitoring wells.

Reynolds et al., (1990) conducted laboratory tests to evaluate the effects of five halogenated hydrocarbons on several casing materials. The halogenated hydrocarbons and casing materials used in the experiment were identical to those used by Reynolds and Gillham (1985) with the addition of glass, SS316, aluminum, and galvanized sheet metal to the casing materials.

The results indicated borosilicate glass was the least likely of the 10 materials to affect the samples. The results also showed that all of the metals had the potential to sort compounds from solution. The order of the compound sorption rate for the metals was galvanized steel > aluminum > SS (greatest to least sorption).

Results of the sorption experiments indicated rigid PVC was preferable to PTFE for sampling low concentrations of halogenated hydrocarbons. The compound sorption rates, from greatest to least sorption, are latex > low density PE > PP > nylon > PTFE > rigid PVC. The rates of compound loss, from greatest to least loss, are PCE > HCE > 1,1,1-TCA > BRO > 1,1,2,2-TET. It should be noted the inequalities shown above are not necessarily significant. For example, the rates between PTFE and rigid PVC are not significant and the same is true for nylon and PP. Their study showed flexible polymer tubing is likely to have greater sorption rates than rigid polymers which is in agreement with Barcelona et al., (1985). They also found evidence that there is a correlation between compound solubility and sorption, substantiating earlier studies. Reynolds et al., (1990) found diffusivity decreased as mean molecular diameter increased which agrees with a study performed by Berens and Hopfenberg (1982), based on polymeric diffusivity tests.

They suggest the use of PTFE in monitoring wells in areas where higher concentrations might be encountered, for instance near a solvent spill. Their study showed a polymer exposed to high concentrations of an organic compound that is a good solvent for the polymer, that the polymer will absorb large quantities of the solvent and swell. However, it is difficult to predict the swelling power of various solvents. As an example, rigid PVC can absorb over 800 percent of its weight in DCM but only 1 percent of CCL_4. Schmidt (1987), however, found no swelling or distortion of rigid PVC casing or screen when exposed to various gasolines for 6.5 months.

Taylor and Parker (1990) visually examined PVC, PTFE, SS304, and SS316 with a scanning electron microscope (SEM) to determine how they were affected by long-term exposures (1 week to 6 months) to organic compounds. Organics used in this test were PDCB, ODCB, toluene, and PCE at concentrations of 17.3, 33.5, 138, and 35.0 mg/L, respectively (approximately 25 percent of their solubilities in water).

SEM examinations showed no obvious surface structure changes for any of the materials exposed to the different

concentrated organic aqueous solutions. They caution, however, that this study cannot be extended to instances where casing materials are exposed to pure organic solvents. They did not report the amount of compound sorbed by the different casing materials.

Inorganic Studies

Massee et al., (1981) studied the sorption of silver (Ag), arsenic (As), Cd, selenium (Se), and Zn from distilled water and artificial sea water by borosilicate glass, high-pressure PE, and PTFE containers. The effect of specific surface (R in cm^{-1}), i.e., the ratio of the surface area of the material in contact with the solution, to the volume of the solution, was also studied. Metals were added to the distilled and artificial sea water. The pH levels of the aqueous solutions used were 1, 2, 4, and 8.5. Water samples were tested at intervals ranging between 1 minute and 28 days. Losses of As and Se were insignificant for all the treatments. At pH levels of 1 and 2, no significant sorption from either distilled water or artificial sea water was observed for any of the containers or metals used in this study. Test results of the sorption of Ag, Cd, and Zn from distilled water and sea water are presented in Tables 7 and 8, respectively.

The results showed PTFE sorbed substantial amounts of Ag, Cd, Zn, and the amounts sorbed were dependent on the pH and salinity of the solutions. Specific surface was found to have a significant effect on the sorption of metals by PTFE. For example, at the end of 28 days the loss of Ag to PTFE with R = 5.5 cm^{-1} was almost 4 times higher than for R = 1.0 cm^{-1}.

Massee et al., (1981) concluded that sorption losses are difficult to predict because the behavior of trace elements depends on a variety of factors such as trace element concentration, material, pH, and salinity. They noted that a reduction in contact time, specific surface, and acidification may reduce sorption losses.

Miller (1982) conducted a study to determine the potential of PVC, PE, and PP to sorb and release Cr(VI) and lead (Pb) when in a Cr(VI)-Pb solution and in a solution of these two metals along with the following organics; BRO, PCE, TCE, trichlorofluromethane, 1,1,1-TCA, and 1,1,2-trichloroethane.

TABLE 7. SORPTION BEHAVIOR OF SILVER, CADMIUM, AND ZINC IN DISTILLED WATER

	Material	PE				Borosilicate Glass				PTFE			
	pH	4		8.5		4		8.5		4		8.5	
	R(cm^{-1})	1.4	3.4	1.0	3.4	1.0	4.2	1.0	4.2	1.4	5.5	1.0	5.5
Metal	Contract Time	Sorption (%)											
Ag	1 hour	10	15	25	36	*	4	9	21	*	*	*	10
	1 day	25	66	72	49	32	18	26	48	4	6	5	25
	28 days	96	100	59	100	82	80	72	63	15	55	22	28
Cd	1 hour	*	*	7	69	*	*	6	26	*	*	7	38
	1 day	*	*	*	47	*	*	10	32	*	*	10	48
	28 days	*	*	*	31	*	*	*	*	*	*	15	46
Zn	1 hour	*	*	*	65	*	*	23	22	*	*	3	16
	1 day	*	*	8	56	*	*	26	22	*	*	5	27
	28 days	*	*	12	56	*	*	*	*	*	*	6	20

**Denotes a loss smaller than 3 percent.*

(Source: Massee et al., 1981)

TABLE 8. SORPTION BEHAVIOR OF SILVER, CADMIUM, AND ZINC IN ARTIFICIAL SEA WATER

	Material	PE				Borosilicate Glass				PTFE			
	pH	4		8.5		4		8.5		4		8.5	
	R(cm^{-1})	1.4	3.4	1.0	3.4	1.0	4.2	1.0	4.2	1.4	5.5	1.0	5.5
Metal	Contract Time	Sorption (%)											
Ag	1 hour	*	*	6	5	*	*	3	3	*	*	*	4
	1 day	*	*	24	28	4	4	6	9	*	*	6	12
	28 days	*	*	46	78	82	71	40	67	*	*	27	37
Cd	1 hour	*	*	*	*	*	*	*	*	*	*	*	*
	1 day	*	*	*	*	*	*	*	*	*	*	*	*
	28 days	*	*	*	*	14	36	*	*	*	*	*	*
Zn	1 hour	*	*	*	*	*	*	9	31	*	*	*	*
	1 day	*	*	*	*	*	*	5	26	4	*	*	*
	28 days	*	*	*	*	20	19	4	9	5	*	*	*

**Denotes a loss smaller than 3 percent.*

(Source: Massee et al., 1981)

TABLE 9. TRENDS OF CHROMIUM (VI) EXPOSED TO SYNTHETIC WELL CASING (COMPARED TO CONTROLS)

	Adsorption		Adsorption/Leaching	
Casing Material	Metals Only	Metals and Organics	Metals Only	Metals and Organics
PVC	No adsorption	Slight (25%) adsorption	No leaching	No leaching
PE	No adsorption	Slight (25%) adsorption	No leaching	No leaching
PP	No adsorption	Slight (25%) adsorption	No leaching	No leaching

(Source: Miller, 1982)

TABLE 10. TRENDS OF LEAD EXPOSED TO SYNTHETIC WELL CASING (COMPARED TO CONTROL)

	Adsorption		Adsorption/Leaching	
Casing Material	Metals Only	Metals and Organics	Metals Only	Metals and Organics
PVC	Mostly (75%) adsorbed	Mostly (75%) absorbed	No leaching	Mostly (75%) absorbed
PE	Moderate (50%) adsorption (delayed)	Moderate (50%) adsorption	No leaching	Mostly (75%) adsorbed
PP	Moderate (50%) adsorption (delayed)	Slight (25%) adsorption	No leaching	Mostly (75%) adsorbed

(Source: Miller, 1982)

Tables 9 and 10, respectively, present the results for the Cr(VI) and Pb adsorption and leaching studies. The results showed that none of the materials tested adsorbed Cr(VI) to any significant extent when in a solution with Pb. When in a solution with Pb and 6 other organics, 25 percent of Cr(VI) was adsorbed by the 3 casing materials. No leaching of Cr(VI) was observed from any of the materials either in the metals only or metals and organics solutions. Seventy-five percent of the Pb was adsorbed by PVC when in a solution with Cr(VI) and also when in a solution of Cr(VI) and the six organics. PE and PP showed about 50 percent adsorption of Pb when in a solution with Cr(VI). The casing materials did not leach any Pb when in a solution with Cr(VI); however, when in a solution with Cr(VI) and 6 organics, the 3 casing materials leached approximately 50 percent of the Pb initially adsorbed. In his study, Miller found that PVC generally causes fewer monitoring interferences with VOCs than PE and PP and that PVC adsorbed and released organic pollutants at a slower rate relative to PE and PP.

Hewitt (1989a) examined the potential of PVC, PTFE, SS304, and SS316 to sorb and leach As, Cd, Cr, and Pb when exposed to ground water. The pH, TOC, and metal concentrations of the solution were varied and samples taken between 0.5 and 72 hours. The study showed that PTFE had the least-active surface and showed an affinity only to Pb (10 percent sorption after 72 hours). PVC and SS leached and sorbed some of the metals tested. PVC was a source for Cd and sorbed Pb (26 percent sorption after 72 hours). The SSs were the most active of the materials tested. SS304 was a source of Cd and sorbed As and Pb. SS316 was also a source of Cd and sorbed As, Cd, and Pb. The study showed results were affected by the solution variables (i.e., pH, TOC, and concentration). SS304 and SS316 showed evidence of corrosion near cuts and welds which may provide active sites for sorption and release of contaminants. Hewitt (1989a) concludes PTFE is the best material for monitoring the metals used in this study whereas, SSs are not suitable. He states that although PVC was affected by Cd and Pb it should still be considered as a useful casing material based on economics, and that when the time between purging and sampling is less than 24 hours, the effects of Cd and Pb on PVC may be of less concern.

Hewitt (1989b) conducted a study to determine the amounts of barium, Cd, Cr, Pb, Cu, As, Hg, Se, and Ag leached from PTFE, PVC, SS304, and SS316 in ground water. Table 11 summarizes the results of the investigation. Results indicate that PTFE was the only material tested not to leach any metals into the ground-water solution. PTFE, however, did show a trend to sorb Cu with time. PVC and SS316 showed a tendency to leach Cd; in addition, these two materials, along with SS304, sorbed Pb. PVC was also shown to leach Cr and provide sorption sites for Cu. SS316 significantly increased the concentration of Ba and Cu in the ground-water solution. SS304 consistently contributed Cr with time to the ground-water solution. None of the well casing materials contributed significant levels of As, Hg, Ag, or Se to the ground water.

TABLE 11. SUMMARY OF RESULTS

	Ba	Cd	Cr	Pb	Cu
Materials that leached >1% of the EPA drinking water quality level in ground-water solutions	SS316 PVC	SS316 PVC	SS304 SS316 PVC	SS304 PVC SS316	NA*
Materials that showed the highest average overall amount of analyte leached	SS316	SS316	SS304	SS304	SS316

*Does not apply

(Source: Hewitt, 1989b)

Hewitt (1989b) concludes PTFE is the best casing material when testing for trace metals while SS should be avoided. He also states PVC is an appropriate second choice because its influence on metal analytes appears to be predictable and small.

Casing Material Cost Comparison

A consideration when installing monitoring wells is cost. Costs to be considered in the installation of monitoring wells are cost of construction materials, drilling costs, and expected life (replacement costs) of the casing material. Table 12 presents a cost comparison among five casing materials: PVC, SS304, SS316, PTFE, and FRE. The prices shown were obtained from Brainard-Kilman (1990) with the exception of the FRE casing, whose price was provided by ENCO (1989). The cost estimates are for ten 10-feet sections (100 feet) of 2-inch threaded casing, 5 feet of 0.010-inch slotted screen, and a bottom plug.

TABLE 12. CASING MATERIAL COST COMPARISON

Prices reflect the cost of ten 10-ft long by 2-in. diameter casing sections, a 5-ft long 0.010-in slotted screen, and a bottom plug.

Casing Material	Price
PVC*	$ 179.50
FRE**	966.00
SS304	1,205.00
SS316	1,896.00
PTFE	3,293.50

** Schedule 40 PVC*

*** Low flow screen*

The cost of materials for 1 PTFE well is approximately 18 times greater than 1 constructed on PVC (Table 12). At first glance, PVC, by far, is the most economical material for constructing monitoring wells. However, if drilling and material (bentonite, cement, sand, etc.) costs are considered, the percent difference in cost between PVC wells and wells constructed of SS, FRE, or PTFE is reduced.

For example, assume that the cost of installing, materials, and completing a 100-feet deep monitoring well (exclusive of casing material costs) in unconsolidated material is $5,000. When the cost of casing material is added to the drilling and materials costs, a PVC-cased well costs $5,179.50 and an SS316-cased well $6,896.00. When drilling and materials costs are considered, a PVC-cased well costs approximately 25 percent less than a SS316-cased well. However, when drilling and materials costs are not taken into account, PVC casing looks especially attractive since it is approximately 90 percent less expensive than SS316 casing. In this case, a SS316-cased well may be considered to be cost effective especially if organics are expected to be sampled. Thus, the significance of the "cost of casing materials versus ground water-casing interaction" issue is reduced.

CONCLUSIONS

All aspects of a ground-water sampling program have the potential to introduce error to a ground-water sample. Interaction between monitoring well casing materials and ground water is only one of the ways in which error may be introduced in a sampling program. Presently, there are a variety of materials available for fabricating monitoring wells. The potential for these casing materials to interact with ground water has found to be affected by many factors, including pH and composition of the ground water and the casing-ground water contact time. The complex and varied nature of ground water makes it very difficult to predict the sorption and leaching potential of the various casing materials. Consequently, the selection of the proper casing material for a particular monitoring application is difficult. This is evidenced by the lack of agreement among researchers on which is the "best" material.

The two main classes of casing materials are metals and synthetic materials. SS304 and SS316 are the preferred metals; whereas, PTFE and PVC are the two preferred synthetic polymer casing materials.

There is no clear choice as to which material is "best" for sampling organics or inorganics; however, the following conclusions can be made from a review of the literature:

1. If metals are to be determined, metallic casing of any type should not be used.
2. If organics in high concentrations are to be determined, SS is preferred and PVC and PTFE are questionable.
3. If metals and low levels of organics are to be determined, PVC and PTFE are acceptable.

Many of the experiments examined the effects of time on the sorption and leaching potential of the various casing materials. The experiments were usually run under laboratory conditions in which distilled or "organic free" water was used and casing materials were subject to contaminants for periods ranging from minutes to months. These experiments, in general, indicate a trend for the materials to be more reactive with the aqueous solutions with time. Experiments showed if the time between well purging and sampling is relatively short, some of the more sorptive materials could be used without significantly affecting sample quality. Studies indicate PVC is a suitable casing material if the time between purging and sampling is less than 24 hours.

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ABBREVIATIONS

1,1-DCA	1,1-Dichloroethane
1,1,1-TCA	1,1,1-Trichloroethane
1,1,2,2-TET	1,2,2,2-Tetrachlorethane
1,2-DCA	1,2-Dichloroethane
2,4,6-TCP	2,4,6-Trichlorophenol
ALS	Acrylonitrile butadiene styrene
Ag	Silver
As	Arsenic
ASTM	American Society for Testing and Materials
BRO	Bromoform
c-1,2-DCE	cis-1,2-Dichloroethylene
CCl_4	Carbon tetrachloride
Cd	Cadmium
$CHCl_3$	Chloroform
Cr	Chromium
Cu	Copper
DCM	Methylene chloride (dichloromethane)
DNT	2,4-Dinitrotoluene
EMSL-LV	Environmental Monitoring Systems Laboratory-Las Vegas
FRP	Fiberglass reinforced epoxy
HCE	Hexachloroethane
Hg	Mercury
HMX	Octabydro-1,2,5,7-tetranitro 1,3,5,7-tetrazocine
m-	Meta
MCB	Chlorobenzene
MDCB	m-Dichlorobenzene
MNT	m-Nitrotoluene
MPL	Maximum permissible levels
NSF	National Sanitation Foundation
o-	Ortho
ODCB	o-Dichlorobenzene
p-	Para
Pb	Lead
PCB	Polychlorinated biphenyl
PCE	Tetrachloroethylene
PDCB	p-Dichlorobenzene
PE	Polyethylene
pH	Hydrogen ion concentration of the solution
pK	Log dissociation constant
PP	Polypropylene
ppb	Parts per billion (by weight)
ppm	Parts per million (by weight)
PTFE	Polytetrafluoroethylene (Teflon®)
PVC	Polyvinylchloride
RCRA	Resource Conservation and Recovery Act
RDX	Hexahydro-1,3,5,7-trinitro-1,3,5-triazine
RVCM	Residual vinyl chloride monomer
Se	Selenium
SEM	Scanning electron microscope
SS	Stainless steel
SS304	Stainless steel 304
SS316	Stainless steel 316
t-1,2-DCE	trans-1,2-Dichloroethylene
TCE	Trichloroethylene
TEGD	Technical Enforcement Guidance Document
TNB	Trinitrobenzene
TNT	2,4,6-Trinitrotoluene
TOC	Total organic carbon
U.S. EPA	U.S. Environmental Protection Agency
VOC	Volatile organic compound
Zn	Zinc

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